CHAPTER 6

Role of Earthworms in Traditional and Improved Low-Input Agricultural Systems in West Africa

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INTRODUCTION

Low-Input Agricultural Systems

Sub-Saharan Africa is the only part of the world where the per capita food production has declined in the last 20 years (IBRD, 1989; Ehui and Spencer, 1990, 1992). Increasing population density has led to an increase in demand for food. Farmers have responded by shortening regenerating fallow periods (Goldman, 1990). Land depreciation, indicated by incomplete restoration of soil fertility and decline in crop yields, is the result (OTA, 1984; Matlon and Spencer, 1984). Cultivation of an increasing proportion of land is thus required, causing a diminishing natural resource base (Ehui and Hertel, 1989; Ehui et al., 1990), as well as the destruction of the natural habitat for plant and animal species.

Small-scale farmers in West Africa have only scarce or no financial resources to purchase agricultural inputs; the few purchased are mainly used for cash crops such as cocoa and coffee. Due to infrastructural, economic, and soil-related problems of pesticide and fertilizer use, high-input, intensive agriculture as in developed countries is rarely practiced (Lavelle et al., 1992). Thus a large portion of arable land is still managed in the traditional way of "slash and burn," with its large land yet low capital and low labor requirements. Social (food supply) and environmental concerns over the continued clearing of forests have led to the development of alternatives to slash and burn.

Innovative systems should permit higher yields for a longer period of continuous cropping, yet should require low or no external inputs while increasing the sustainability of the land-use system. Two possibilities are alley cropping (Kang et al., 1984) and live mulch systems (Akobundu, 1980, 1984). In alley cropping, food crops are grown between hedgerows of trees or shrubs that are pruned during the cropping phase. A live-mulch system consists of a herbaceous legume species interspersed with food crops. During cropping, the herbaceous legumes are slashed. In both systems cutting the biomass reduces competition and provides soil-protecting mulch and nutrients. Slashing of live mulch also prevents climbing species from overgrowing and breaking the crop. Both systems are supposed to achieve higher nutrient recycling and use-efficiency through a multi-layered, deep-reaching root system and the use of phases in which food crops cannot be grown. A second aspect is the option of a controlled fallow and the immediate presence of a soil-regenerating species after cropping.

Both systems have been investigated over a number of years and permit higher yields (Mulongoy and Akobundu, 1985; Kang et al., 1990; Lathwell, 1990; Hauser and Kang, 1993; Kühne, 1993) and longer continuous cropping, yet reduced fertilizer inputs. Establishment of these systems requires little or no capital investment, but might increase the total demand for labor, cause seasonal shifts in labor allocation, and need some managerial skills. Farmer-participatory research on-farm has shown that alley cropping is a suitable option (Akonde et al., 1989; Getahun and Jama, 1989; Parera, 1989). However, neither system permits continuous cropping without declining yields and soil degradation, although the decline is slower than in traditional slash and burn (Van der Meersch, 1992; Hauser and Kang, 1993).

Past research has focused mainly on aboveground properties and performance of the vegetation, and very little information has been gathered on below-surface features of improved, as well as traditional, cropping systems (Lal, 1991). The latter is particularly true for soil biological activity, especially for the soil macrofauna, including earthworms (Brussaard et al., 1993).

The Potential of Earthworm Activity

Soil-related constraints, such as low inherent fertility, usually limit crop production in the more humid areas of West Africa. Crop nutrition thus relies on biological processes that are mediated by teams of soil fauna in which earthworms play important roles. If soils are to be managed so that their biological capacity for nutrient cycling and maintenance of soil structure is retained, then more attention should be paid to the effect of cultivation and cropping practices on earthworms (Springett et al., 1992).

Earthworms' important role in soil profile development (Bouché, 1981), soil restoration, and maintenance of soil properties has been shown for a wide range of conditions (Edwards and Lofty, 1972; Satchell, 1983; Lee, 1985; Blanchart, 1992). However, earthworms are not primary producers, but trans-

form and translocate soil, soil organic matter, and plant nutrients, so they depend on the vegetation and other organisms to provide food sources and favorable biophysical conditions. A large number of publications recently summarized by Lavelle (1994) describe the beneficial effects of earthworm activity and their casts on soil properties, plant growth, and ecosystem stability.

Earthworm activity has physical and biochemical consequences for agriculture. Earthworms burrow, improving macroporosity (Brussaard et al., 1990; Marinissen and Dexter, 1990) and infiltration properties (Ehlers, 1975; Douglas et al., 1980; Lal, 1987; Casenave and Valentine, 1989). While burrowing, they ingest large amounts of soil and plant residue. In Lamto, Cote d'Ivoire, Megascolecidae, and Eudrilidae species consume 6.7 g dry weight per 1 g individual per day. Of this, 99.9% is egested as casts (Lavelle, 1974) deposited at the surface, in burrows or in other macropores.

Casts usually contain more organic carbon, total nitrogen, and exchangeable cations than the surrounding topsoil (De Vleeschauwer and Lal, 1981; Lal and De Vleeschauwer, 1982; Mulongoy and Bedoret, 1989; Fragoso et al., 1993; Hauser, 1993). Casts also have higher microbial populations and enzyme activity than the ingested soil (Gorbenko et al., 1986; Tiwari et al., 1989; Barois et al., 1993; Tiwari and Mishra, 1993). There is some evidence that earthworms preferentially ingest smaller soil particles, so casts contain more clay and silt and less sand than the soil in which they live (Nye, 1955; Watanabe, 1975; Sharpley and Syers, 1976; Lavelle et al., 1992; Hauser, 1993).

Since agricultural production is usually accompanied by a major disturbance of the natural ecosystem, three basic questions need to be answered to assess the role of earthworms in sustainable, low-input agricultural systems:

1. Does earthworm activity make a significant contribution to the sustainability of natural ecosystems?
2. What are the key factors affecting their survival and activity?
3. Can management techniques be manipulated to maintain activity during phases of disturbance such as cropping?

Little or no information is available to answer all three questions for traditional and alternative cropping systems within one particular environment. This paper reports on a series of field experiments and investigations on earthworm activity in a subhumid and a humid tropical environment in West Africa.

Surface Casting as an Index of Earthworm Activity

Earthworm activity includes burrowing, ingesting soil, transforming it, and exporting it as casts. Activity has previously been described by using biomass of surface litter removed (assuming earthworms are the only organisms doing this), volume and length of burrows excavated, and numbers or dry weight of casts. However, the majority of studies have quantified activity using number

and/or biomass of worms expelled from the soil. This assumes that the volume of burrows excavated, soil ingested, and casts egested by a population of worms is proportional to its size. Yet recent research shows that these are significantly affected by food quality, soil moisture levels, and temperature (Martin and Lavelle, 1992; Kretzschmar and Bruchou, 1991).

The use of casting as an index of activity has a number of advantages. Casting is an actual expression of egestion which is correlated to ingestion in nutrient-poor soils. Sampling is nondestructive, allowing repeated measurements in the same field area over time. In contrast, assessing the volume of burrows excavated in the field is only possible by destructive measures. It is not easy to assess the quantity of subsurface casts or its significance in aggregate formation and soil structure (Lee, 1985), but those deposited at the surface are easy to quantify, have a more significant effect on soil structure and profile development (Bouché, 1981), and minimize the risk of soil losses through surface runoff and erosion (Hauser, 1990). Surface casting species are known among all the families of earthworms (Lee in Satchell, 1983). Syers et al. (1979) reported that surface cast production was correlated to removal of surface litter, thus confirming the strong link between surface casting and earthworm activity. Surface casting as an index is also suggested by Edwards and Lofty (1972).

MATERIALS AND METHODS

Experiments and observations were conducted between 1990 and 1994 at IITA headquarters, Ibadan (7° 31′ N and 3° 54′ E), southwestern Nigeria, and at the IITA Humid Forest Station, Mbalmayo (3° 51′ N and 11° 27′ E), southern Cameroon. The annual rainfall at Ibadan is 1200 mm, with a bimodal distribution. Rains commence in April, followed by a short dry season during August, then recommence in September, and stop at the end of October. Soils are mainly Alfisols (Oxic Paleustalf) on the upper slopes and Entisols (Psammentic Ustortent) on the lower slopes and in valleys (Moormann et al., 1975). At Mbalmayo annual rainfall is 1520 mm, with a bimodal distribution. Rains commence in March and end in early July, followed by a short dry season of 6 to 8 weeks, then recommence in September, and stop at the end of November. The soil is classified as a clayey, kaolinitic, isohyperthermic, Typic Kandiudult (Hulugalle and Ndi, 1993). At both sites vegetation is humid, semi-deciduous, mature and young secondary forest. At both sites field experiments were conducted only on manually cleared land. At Mbalmayo casting activity was monitored in undisturbed secondary forest that had not been cultivated for at least 20 years. This was compared with activity in slashed-and-burned fields planted to an intercrop of maize, cassava, groundnut, and plantain. At Ibadan, forest and natural bush regrowth were compared with alley cropping using *Leucaena leucocephala, Senna siamea* or *Dactyladenia barteri* as hedgerow species and herbaceous legume live mulch using *Pueraria phaseoloides.* All

data on earthworm casting activity were obtained using a continuous sampling method. Surface casts were collected once or twice per week from framed microplots. Casts were dried at 65°C after each sampling and analyzed after the end of the casting season.

RESULTS AND DISCUSSION

Methodological Aspects of Monitoring Earthworm Activity

The literature on earthworm activity in West Africa provides a wide range of data from various environments; however, there is no common methodology for calculating total annual soil ingestion and cast deposition. For example, if casting levels for sampling that does not cover the whole season are extrapolated, serious errors may occur because of pronounced phases of casting and no-casting (for Ibadan, see Figure 1). As a result, data are wide-ranging, although this may be caused by environmental conditions.

Sampling frequency is another critical issue. Fresh casts and casts that have not dried at least once are not very stable and can easily be destroyed by rain. A high sampling frequency is thus required to reduce the risk of underestimating casting. In an experiment where the impact of rain was reduced by 2-mm mesh screen and cotton cloth, cast recovery at weekly samplings was increased by 21.8% compared with plots receiving rain at full impact (Figure 2).

When comparing casting in a different ecosystems such as forests vs. cropped fields, the effect of altered raindrop size on casts must be considered. Although the amount of throughfall is lower in forests, the drop size and therefore the detachment capacity is higher (Evans, 1980; Lal, 1987), and a higher rate of cast disintegration in forests can be expected. Conversely, a live mulch with a multi-layered canopy close to the soil surface such as in *P. phaseoloides* live mulch might greatly reduce mechanical disintegration. Thus amounts of casts collected are probably lower than the amounts deposited. The potential errors increase with decreasing ground cover and increasing canopy height.

Earthworm Species and Their Distribution

Earthworms are widespread in West Africa except where the mean annual rainfall is less than 800 to 1000 mm and the dry season exceeds 3 to 5 months (Lavelle, 1983). More than 28 genera are represented (Table 1). In Ibadan, the most frequently found species in descending order of importance are *Hyperiodrilus africanus,* and *Eudrilus eugeniae*. *H. africanus* is a surface casting species reported not to feed on litter at the surface (Madge, 1965). In the forest and in newly cleared sites a large species of up to 30 cm length was found.

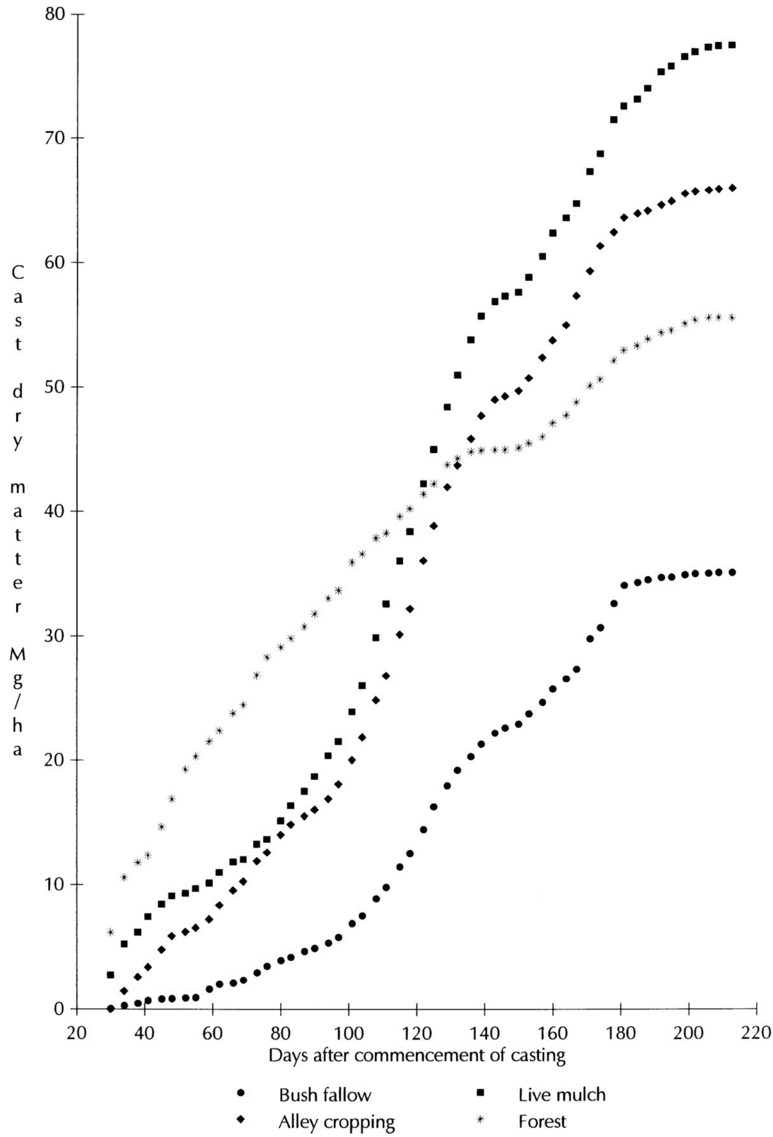

Figure 1 Annual cumulative amount of casts deposited at the soil surface — Ibadan, Nigeria, 1992.

This species is yet to be identified. It is not very abundant and is not found in older fields.

The two dominant species are not uniformly distributed between cropping systems. In newly cleared fields, both are abundant. However, with an increasing number of years of cropping and under conditions exposing the soil surface

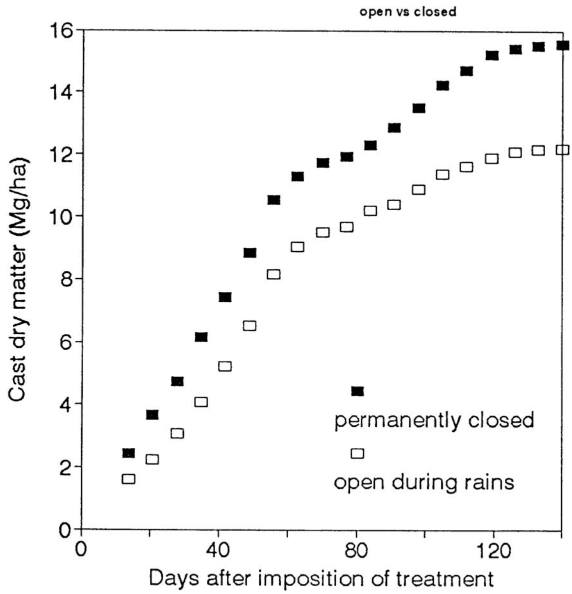

Figure 2 Cumulative amount of casts recovered from plots permanently covered with screen or cotton cloth vs. plots kept open during rains.

for a long time to direct radiation and full impact of rain, *H. africanus* disappears, while *E. eugeniae* becomes dominant. Yet, where mulch is provided and a cover crop is grown, or near trees in alley-cropping systems, both species remain abundant and *H. africanus* continues to be dominant.

Two basic types of surface casts are found: pipe-shaped casts with a vertical hole running through the length, sealed at the top; and those composed of fine granular pellets stuck together. Madge (1969) found that these are species specific; the former egested by *H. africanus* and the latter by *E. eugeniae.* At Mbalmayo casts similar to the *H. africanus* casts but larger in diameter are found. However, the dominant species producing these casts is yet to be identified.

Earthworm Activity in Relatively Undisturbed Environments

Kollmannsperger (1956) reports of 25 to 30 Mg ha^{-1} surface casts annually in the Cameroonian mountain savannah. Madge (1969) calculated an annual surface cast production of 30 to 240 Mg ha^{-1} in grassland in southwestern Nigeria. Lal and Cummings (1979) estimated cast deposition of 328 Mg ha^{-1} yr^{-1} in a forest in southwestern Nigeria. Lavelle (1978) reports of 278 Mg ha^{-1} yr^{-1} of surface casts in grass savannah, while Beauge (1912) found 268 Mg ha^{-1} yr^{-1} in grassland in Sudan Gezira (adapted in Lee, 1985). Very little is known about earthworms' contribution to organic matter turnover and nutrient cycling or their impact on soil texture and structural stability in their natural undisturbed environments.

Table 1 Genera of Earthworms That Have Been Found in West Africa Using Gates' System of Classification

Family	Genus	Areas where identified
Ocnerodrilidae	*Nannodrilus* (Beddard)	Western tropical Africa
	Nematogenia (Eisen)	Southern Nigeria, Liberia
Octochaetidae	*Millsonia* (Beddard)	Guinea, Nigeria
	Monogaster (Michaelson)	Southern Cameroon
	Neogaster (Cernosvitoz)	Nigeria
Eudrilidae sub-family Parendrilinae	*Chuniodrilus* (Michaelson)	Liberia
	Legondrilus (Sims)	Ghana
	Libyodrilus (Beddard)	Cameroon
	Scolecillus (Omodeo)	West Africa
	Stuhlmannia (Michaelson)	West Africa
	Beddardiella (Michaelson)	Nigeria, Cameroon
	Buettneriodrilus (Michaelson)	Eq. West Africa
	Eminoscolex (Michaelson)	Cameroon
	Ephyriodrilus (Sims)	Southern Nigeria
	Eudrilus (Perrier)	West Africa
	Euscolex (Michaelson)	Cameroon
	Eutoretus (Michaelson)	North Nigeria
	Haaseina (Michaelson)	West Africa
	Heliodrilus (Beddard)	West Africa
	Hippopera (Taylor)	West Africa
	Hyperiodrilus (Beddard)	Togo, S. Nigeria
	Iridodrilus (Beddard)	Cameroon
	Kaffania (Michaelson)	Cameroon
	Keffia (Clausen)	West Africa
	Parascolex (Michaelson)	Cameroon, Togo
	Rosadrilus (Cognetti)	Cameroon
	Teleutoreutus (Michaelson)	West Africa
Microhaetidae	*Alma* (Grube)	Cameroon, Nigeria, Togo

Adapted from Edwards, C. A. and Lofty, J. R., 1977. *Biology of Earthworms,* 2nd ed., Chapman and Hall, London, p. 333.

In Ibadan, the forest is the least disturbed ecosystem followed by fallow land of decreasing fallow length, representing systems with increasing impact of human activity. An experiment was set up in Ibadan to compare surface casting in the forest with various 3-year fallow systems: bush regrowth, *Leucaena leucocephala* fallow, and *Pueraria phaseoloides* fallow. Although locally and in very small areas, casting of more than 300 Mg ha^{-1} was observed, the average annual cast deposition was 38.5 Mg ha^{-1} in the forest and 80 Mg ha^{-1} in the bush regrowth (Table 2). In the *L. leucocephala* fallow, casting was 33% higher than in the forest. In the *P. phaseoloides* live mulch reported here, invasion by carnivorous ants drastically reduced the earthworm population at the start of the season. This indicates that the least disturbed system does not provide the best conditions for maximum surface casting, organic matter turnover, and nitrogen cycling. This might result from characteristics of the soil moisture regime under forests. During dry phases soil water tension in the top 50 cm increased faster under forests than under the other treatments

Table 2 Annual Cast Deposition and Amount and Concentration of Organic Carbon and Total Nitrogen from Forests and 3-Year-Old Fallows on Alfisols, Ibadan, 1991

	Casts (Mg ha^{-1})	Org. C (kg/ha)	Ttl. N (kg/ha)	Org. C (%)	Ttl. N (%)
Forests	38.5	2619.5	213.0	6.74	0.55
Bush regrowth	80.2	3699.2	360.7	4.52	0.45
L. leucephala regrowth	51.1	2924.5	243.3	5.51	0.46
P. phaseoloides regrowth	19.8[a]	1376.7	125.0	6.92	0.62

[a] Earthworm population drastically reduced by carnivorous ants.

(Figure 3). This might have caused an earlier retreat of worms to deeper layers and, consequently, less activity near the surface. Martin and Lavelle (1992) showed in simulations that soil water content is a key factor in earthworms' vertical movements.

The amount of organic carbon in casts represents 5.0 to 11.6% of the total organic carbon, while the total nitrogen in casts ranges between 5.3 and 12.9% of the total in the top 0 to 15 cm of the soil profile (Table 3). Thus earthworm casting activity involves a considerable proportion of the soil carbon and nitrogen pool in two of the fallow systems. The comparatively low proportions

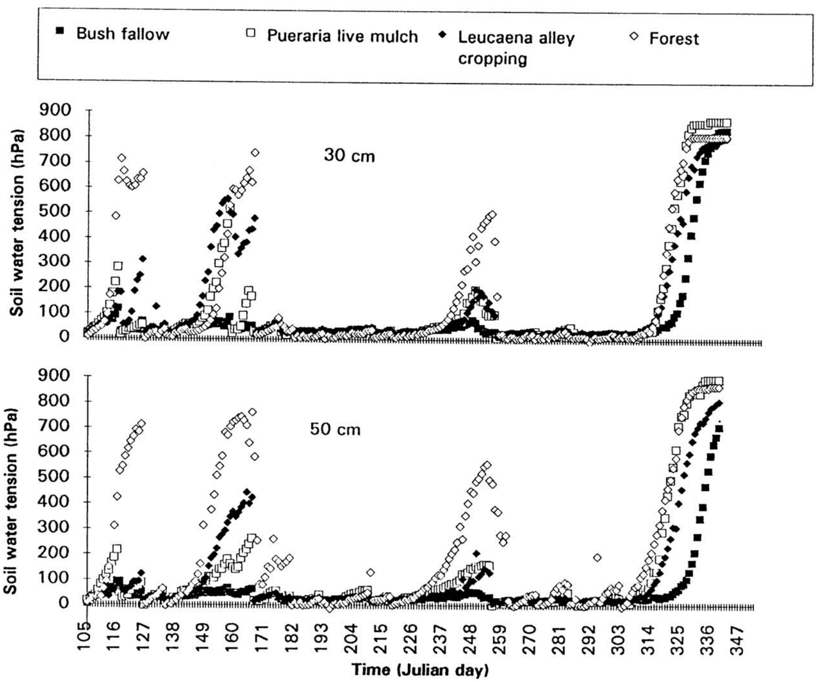

Figure 3 Soil water tension at 30 and 50 cm depth under forest and fallows — Alfisol, Ibadan, Nigeria, 1991.

Table 3 Amounts of Organic Carbon and Total Nitrogen in the 0 to 15 cm Topsoil and Proportion Contained in Earthworm Casts — Alfisol, Ibadan, 1991

	Soil organic C ($Mg\ ha^{-1}$)	Soil total N (kg/ha)	Percentage in casts	
			Org. C	Ttl. N
Forests	54.6	3192.2	5.74	6.67
Bush regrowth	32.5	2803.7	11.38	12.86
L. leucephala regrowth	25.3	2099.1	11.58	11.59
P. phaseoloides regrowth	27.4	2357.9	5.03[a]	5.30[a]

[a] Earthworm population drastically reduced by ants.

in the casts from forest soil relate to the very high amounts of organic carbon and nitrogen in the forest soil. The low values in *P. phaseoloides* live mulch are due to the low casting activity, since the chemical properties of the casts would have resulted in a similar or higher proportion if the amount of casts had been comparable with that in the forest soil.

Relating the amounts of carbon and nitrogen incorporated in casts to the soil carbon and nitrogen pool does not reflect the importance of earthworm activity in other processes of nutrient recycling and organic matter turnover. However, the above figures indicate that earthworm casts are more important after forest clearance since they contain a greater proportion of the soil nutrients as soil carbon and nitrogen pools decline. The performance of earthworms should be related to processes like biomass production of the vegetation, nutrient accumulation in biomass, decomposition of biomass, and release of nutrients. Such investigations were not possible in the forest and during the regrowth phase of fallows, but data are available from cropped fields and are reported later in this chapter.

Impact of Slash-and-Burn Land Preparation and Cropping on Earthworm Activity

Human activity can change biophysical conditions drastically as is the case when forests or fallows are cleared to grow food crops (Critchley et al., 1979; Lal, 1986). Little is known about the immediate impact on earthworm activity of converting forest or fallow into arable land.

In 1992 the three fallows mentioned above were cleared and the bush regrowth, as well as the *P. phaseoloides,* completely burned. In *L. leucocephala* alley cropping, only the understorey was burned, but the *L. leucocephala* was cut after the burn and left on the plots until the leaves were shed. Wood was then removed, and all plots were planted to maize/cassava intercrop. In the same experiment were permanently cropped plots under the same fallow managements. They had been cropped for the previous 3 years and were entering the fourth year of cropping.

Table 4 Casting Activity, Organic Matter Accumulation, and Nutrient Recycling in Newly Cleared (New) Vs. Permanently Cropped (Perm.) Fallow Management Systems and Secondary Forest — Alfisol, Ibadan, Nigeria, 1992

	Casts (Mg ha^{-1})	Org. C (kg/ha)	Ttl. N (kg/ha)	Exch. Ca (kg/ha)	Exch. Mg (kg/ha)
Forest	75.0	5395	407.1	283.9	47.8
Bush fallow perm.	60.0	2622	200.0	178.3	24.0
Bush fallow new	28.8	1679	94.1	72.3	14.5
Alley cropping perm.	91.6	4501	322.4	250.0	39.8
Alley cropping new	59.4	3170	246.1	203.0	26.2
Pueraria mulch perm.	86.3	4554	351.6	321.2	27.3
Pueraria mulch new	55.2	2764	212.4	171.4	43.3

Casting activity and the amount of organic carbon and nutrients in casts were higher in the permanently cropped plots than in newly cleared plots for all management systems (Table 4). Of the permanently cropped treatments, the two improved fallow management systems had the highest casting, exceeding that in the forest. Chemical properties of casts from the forest were enriched in nutrients and organic carbon compared with casts from cropped fields (Table 5). Only exchangeable magnesium was higher in the permanently cropped *P. phaseoloides* live mulch system.

Lower casting activity in newly cleared compared with permanently cropped plots is an unexpected result. It indicates that drastic environmental change severely disrupts earthworms. Deep infiltration through macropores of rain, high in pH from dissolving ash, apparently has a detrimental effect on casting activity. The negative impact of ash on casting was confirmed in separate experiments (Asawalam, unpublished). However, the heat from burning could not have had an effect since the burning was performed before the worms appeared in the surface soil.

Exposure of the soil surface to direct radiation during clearance may also be significant. The importance of ground cover or shading for high casting

Table 5 Chemical Properties of Earthworm Casts from Newly Cleared (New) Vs. Permanently Cropped (Perm.) Fallow Management Systems and Secondary Forests — Alfisol, Ibadan, Nigeria, 1992

	Org. C (%)	Ttl. N (%)	Exch. Ca (cmol[+]/kg)	Exch. Mg (cmol[+]/kg)
Forests	7.05	0.545	19.0	5.2
Bush fallow perm.	4.39	0.336	14.6	3.3
Bush fallow new	5.57	0.373	13.9	4.2
Alley cropping perm.	4.83	0.355	13.5	3.3
Alley cropping new	5.35	0.435	17.5	3.6
Pueraria mulch perm.	5.23	0.405	18.7	2.6
Pueraria mulch new	4.90	0.377	15.8	6.4

activity has been shown by Franzen (1986) and Hauser (1993). Weeds, crop residues, slashed *P. phaseoloides,* and *L. leucocephala* prunings provided ground cover in the early phases of crop development. The possible increase in food supply from decomposing roots apparently does not compensate for the negative impact of exposure to the sun. This agrees with Hauser (1993) who demonstrated that shade is more important than food supply.

In Mbalmayo, casting was severely reduced in the cropped fields. Mean annual casting was 2.82 Mg ha^{-1}, while in the adjacent forest it was 9.3 Mg ha^{-1}. In plots maintained bare on the field periphery only 0.87 Mg ha^{-1} of casts were recorded.

Performance of Earthworms in Permanently Cropped Fields

Casting activity and nutrient cycling in cropped fields can exceed that in forests (Table 4). Management practices such as burning vs. mulching apparently have a major impact. Over time, however, activity declines in all cropping systems (Figure 4). The regression suggests that casting is initially higher under alley cropping than in the traditional system without trees. Unfortunately, there are no data available on casting activity in the first 3 years after clearing without the impact of burning. Thus it might be that in traditional systems a more rapid decline in casting occurs in the first few years, while it declines more steadily in alley cropping. As casting activity was higher in the alley cropping treatment (cleared from the forest 3 years before) than in the

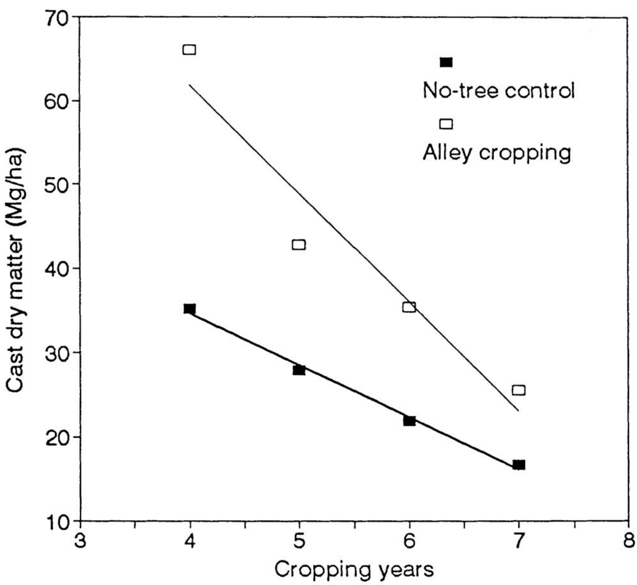

Figure 4 Annual earthworm casts deposition at the surface as a function of cropping years.

Table 6 Dry Matter Production, Nitrogen Concentration and Accumulation, Amount of Residues at the Onset of Rains, and Root Density During the Rainy Season of *P. phaseoloides* Live Mulch and *L. leucocephala* Alley Cropping on Alfisol, Ibadan, Nigeria

Species	Biomass ($Mg\ ha^{-1}$)	Nitrogen (%)	Nitrogen (kg/ha)	Residues ($Mg\ ha^{-1}$)	Root[b] density/1500 cm^2
Pueraria	5.62	2.02	113.6	4.15	262.0
Leucaena[a]	4.50	4.19	188.5	0.51	48.2

[a] Excluding wood.
[b] Counted on surface of a trench, 0 to 150 cm depth.

forest (Table 4), there was a net increase in casting during the 3 years of treatment.

To use earthworm activity for sustaining soil fertility, factors that stimulate casting activity in improved fallow and cropping systems need to be determined. Both *P. phaseoloides* live mulch and alley cropping provide additional biomass to the production of the weeds and food crops. Average *P. phaseoloides* biomass production on an Alfisol was 5.62 Mg ha^{-1} (Table 6) with a maximum of 9.0 Mg ha^{-1}. Maximum dry matter production was attained relatively late in the year (end of November), so that a large amount of biomass was retained throughout the dry season until the onset of rains. Alley cropping with *Leucaena leucocephala* on an Alfisol produced on average, 8.63 Mg ha^{-1} dry matter. This amount comprised 52% leaves and small twigs and 48% woody stems. Nutrient release and decomposition of the two materials are probably quite different because *L. leucocephala* leaves had twice as high a nitrogen concentration of *P. phaseoloides.*

On the more fertile Alfisols, the differences in biomass production and litter retention did not cause a pronounced difference in casting activity between *P. phaseoloides* live mulch and alley cropping. The 30% lower casting activity in bush fallow regrowth might be caused by the lack of litter and pruning inputs. On the less fertile sandy Entisols, however, the positive effect of the more persistent litter of *P. phaseoloides* and the possibly higher fine-root turnover permitted casting activity almost twice that in alley cropping. Lack of sufficient ground cover and biomass input in the bush fallow regrowth led to a 75 to 86% reduction in casting, as compared with alley cropping and *P. phaseoloides* live mulch, respectively (Table 7).

Table 7 Amounts of Casts, Organic Carbon, and Total Nitrogen Deposited at the Soil Surface — Entisol, Ibadan, 1992

	Casts ($Mg\ ha^{-1}$)	Organic C (kg/ha)	Total N (kg/ha)
Forests	36.5	1805.4	131.5
Bush fallow system	10.4	412.6	27.5
Leucaena alley cropping	40.6	1903.6	136.6
Pueraria live mulch	60.0	2896.9	221.5

On the comparatively poor Ultisol at Mbalmayo no surface casting was observed in the third year of alley cropping using *Senna spectabilis, Dactyladenia barteri,* or *Flemingia macrophylla* as hedgerow trees. The only crop maintaining surface casting was plantain, but it was restricted to the close vicinity of the corm, which is heavily mulched with the residues of harvested plants.

The results indicate that cropping systems targeted at more sustainable use of the soil resource can only be developed if the interdependencies between soil type and the most compatible vegetation are known and considered. They also show that earthworms react more sensitively to disturbance on less fertile soils.

Spatial Heterogeneity of Earthworm Activity in Alley Cropping

In alley cropping the supply of food through aboveground prunings is equal at all positions in the system, while the persistence of shade varies over time and distance from hedgerows. Only in the immediate vicinity of the hedgerows is the soil shaded all year round, and it was there that the highest casting activity was found in all alley cropping experiments (Table 8). In all *L. leucocephala* alley cropping systems older than 1 year, casting significantly declined toward the middle of the interrow space. When using *Senna siamea* or *Dactyladenia barteri,* producing a more recalcitrant litter, the decline was less pronounced but still significant in *Senna siamea.* Only on nondegraded soil was casting activity in the middle of the interrow space significantly higher than in a system without trees.

In alley cropping the biological degradation process occurs at two contrasting locations with two different rates. Casting activity did not differ between 4-, 5-, and 6-year-old alley cropping systems under the hedgerows.

Table 8 Annual Casting Activity in Alley Cropping Under the Hedgerow (Row) and in the Interrow Space (Middle) as Compared with Casting in a No-Tree Control

		Casts (Mg ha^{-1})			
Hedgerow species	Cropping years	Row	Middle	No-tree	LSD 0.05
Leucaena leucocephala	1[a]	63.9	56.0	27.4	18.7
Leucaena leucocephala	4[a]	113.9	60.6	35.2	15.2
Leucaena leucocephala	5[b]	116.8	24.3	27.8	7.8
Leucaena leucocephala	6[c]	49.9	14.1	15.6	23.7
Leucaena leucocephala	6[b]	112.8	23.1	21.8	46.2
Dactyladenia barteri	6[b]	50.5	36.6	21.8	16.7
Leucaena leucocephala	7[c]	93.1	12.7	16.6	47.6
Senna siamea	7[c]	77.2	19.4	16.6	30.8

[a] Nondegraded.
[b] Moderately degraded.
[c] Severely degraded soil when alley cropping was implemented.

Table 9 Total Amounts of Casts Deposited at the Soil Surface in Alley Cropping and Amounts of Organic Carbon and Nutrients in Alley Cropping and No-Tree Control

		Alley cropping			No-tree	
Hedgerow species	Cropping years	Casts (Mg ha^{-1})	Org. C (kg/ha)	Ttl. N (kg/ha)	Org. C (kg/ha)	Ttl. N (kg/ha)
Leucaena leucocephala	1[a]	53.5	2527	200	1420	89
Leucaena leucocephala	4[a]	66.1	3202[d]	230	1518	114
Leucaena leucocephal	5[b]	42.8	1510[d]	138[d]	490	46
Leucaena leucocephala	6[c]	23.5	857	85	501	37
Leucaena leucocephala	6[b]	35.3	1743[d]	138	625	48
Dactyladenia barteri	6[b]	36.4	1555[d]	89	625	48
Leucaena leucocephala	7[c]	25.5	1160	89	411	28
Senna siamea	7[c]	31.4	1371	96	411	28

[a] Nondegraded.
[b] Moderately degraded.
[c] Severely degraded soil when alley cropping was implemented.
[d] Significantly different (*p*, 0.05) from respective values in no-tree control.

Under moderately and severely degraded soil conditions the application of prunings in the interrow space had no significant effect. Since the immediate vicinity of the hedgerow is only a small portion of the alley cropping system, the weighted casting activity of the whole system was closer to the amounts found in the interrow space (compare Tables 8 and 9). Chemical properties of casts did not significantly differ between positions in alley cropping, so that organic carbon and total nitrogen were distributed as heterogeneously as the amounts of casts. Weighted-average deposition of organic carbon and total nitrogen was generally higher in alley cropping, but the differences between alley cropping and the no-tree control were significant in only a few cases. Thus alley cropping does not maintain high casting activity over time. Narrowing interrow distances or the introduction of a cover crop as suggested by Hauser (1993) might be required to reduce soil degradation between hedgerows, but might reduce crop yield to unacceptably low levels.

Contribution of Earthworm Activity to Soil Organic Matter and Nitrogen Turnover

The organic carbon and total nitrogen concentrations in the casts of *H. africanus* generally exceeded those in the corresponding topsoil. The increase of organic carbon in casts is relatively higher on soils of lower carbon content, and increments decrease with increasing soil carbon content (Figure 5). *H. africanus* has a particularly high potential to improve soil properties of poor soils, as long as other physical (shade) conditions permit a high level of activity. Madge (1965) reports that *H. africanus* does not feed on surface litter, so it is important to determine whether the increased organic carbon in casts is caused by concentration of soil organic matter through preferential uptake or

whether *H. africanus* incorporates decomposers and decomposing fresh inputs to form new soil organic matter.

Ideally, earthworm activity should be evaluated in comparison with all other processes contributing to the maintenance of favorable soil properties. The primary and thus most important process in this respect is the biomass production of the vegetation and its nutrient accumulation (including nitrogen fixation). Most other factors depend on this primary production. It is very difficult to quantitatively determine and separate the turnover rates for organic carbon and nitrogen of all individual processes involved in a particular ecosystem. We shall attempt to show the relationship between biomass production and nutrient accumulation of the vegetation and the turnover or incorporation of organic and total nitrogen into earthworm casts, here called the apparent incorporation rate (*AIR*), estimated by Equations 1 and 2.

$$AIR_{org\ C} = \text{org C in casts/org C in biomass} \cdot 100 \tag{1}$$

$$AIR_{ttl\ N} = \text{total N in casts/total N in biomass} \cdot 100 \tag{2}$$

Relating the measured amounts of nitrogen and organic carbon in the annual cast production to those in the aboveground biomass production or surface application of hedgerow prunings shows that with increasing the length of cropping and thus soil degradation the apparent incorporation rate decreases (Table 10). On nondegraded soil, apparent incorporation rates were generally above 100%. Under *P. phaseoloides* live mulch, more than three times more nitrogen was accumulated in casts than was determined in the aboveground *P. phaseoloides* biomass.

Table 10 Apparent and Corrected Incorporation Rate of Total Nitrogen and Organic Carbon of Aboveground Organic Inputs Through Vegetation in Earthworm Casts

		Incorporation rate			
		Apparent		Corrected	
Cropping system	Cropping years	Ttl. N	Org. C	Ttl. N	Org. C
Leucaena alley cropping	1[a]	197.1	248.4	142.8	182.1
Pueraria live mulch	1[a]	186.3	109.2	67.0	70.9
Leucaena alley cropping	4[a]	170.9	222.2	115.2	161.1
Pueraria live mulch	4[a]	309.5	180.1	207.0	124.1
Leucaena alley cropping	5[b]	49.1	47.8	29.9	32.9
Leucaena alley cropping	6[b]	66.6	72.5	49.6	57.0
Dactyladenia alley cropping	6[b]	74.4	50.8	55.4	39.4
Leucaena alley cropping	7[c]	70.9	79.7	55.4	61.7
Senna alley cropping	7[c]	54.0	52.8	40.6	39.4

[a] Nondegraded.
[b] Moderately degraded.
[c] Severely degraded soil.

The apparent incorporation rate can only indicate the potential for carbon and nitrogen retention in casts. To get a more accurate estimate of the actual incorporation of carbon and nitrogen, it is necessary to consider the portion of C and N taken up from the soil. For *H. africanus* no information is available onto what extent the worm ingests soil-borne carbon and nitrogen vs. carbon and nitrogen from decomposing dead or applied fresh material. For simplicity, it may be assumed that the earthworms take up soil at its original C and N concentration and, additionally, ingest decomposers and decomposing material originating from litter, root turnover, and applied fresh materials, which are not considered soil organic matter. The difference between cast and soil organic carbon and total nitrogen concentrations would be the portion obtained from these new organic inputs, or would be "nonsoil-borne." In combination with the amount of casts and C and N contents in the biomass the corrected incorporation rate (*CIR*) is estimated by Equations 3 and 4.

$$CIR_{org\ C} = [(\%\ \text{org C in casts} - \%\ \text{org C in soil}) \cdot \text{cast dry matter}]/\text{org C in biomass} \cdot 100 \quad (3)$$

$$CIR_{ttl\ N} = [(\%\ \text{ttl N in casts} - \%\ \text{ttl N in soil}) \cdot \text{cast dry matter}]/\text{ttl N in biomass} \cdot 100 \quad (4)$$

The proportion of nonsoil organic carbon in casts ranged from 69 to 79%, the proportion of nonsoil total nitrogen from 61 to 78%. There was a tendency toward higher proportions of nonsoil carbon and nitrogen with increasing soil degradation and length of cropping (compare with Figure 5).

On nondegraded soil cleared from forest, even after 4 years still more carbon and nitrogen were available for uptake by worms than were provided by aboveground organic inputs (Table 10). This might indicate that there is still a high amount of subsurface material decomposing and being taken up by earthworms. Incorporation of nitrogen in casts was highest in *P. phaseoloides* live mulch, which might be an indication of a high root and nodule turnover. On degraded soils, earthworm activity can incorporate one- to two-thirds of the carbon from organic inputs. The incorporation of nitrogen is slightly lower. The method used here cannot identify the actual sources of carbon and nitrogen. Investigations on the food source of *H. africanus* have only been of a qualitative nature (Madge, 1969) and did not distinguish between soil organic matter and decomposing new inputs.

In an experiment where ^{15}N-labeled *L. leucocephala* and *D. barteri* prunings were applied, the average percentage of nitrogen in casts derived from *L. leucocephala* was 14.2% (4.6 to 18.2%), while the average percentage of nitrogen derived from *D. barteri* was 5.5%, ranging from 1.5 to 9.0%. These figures were obtained from a 6-year-old alley cropping experiment and are therefore of limited representation. However, it appears that *H. africanus* draws predominantly on the more decomposed soil resource pool, rather than on the

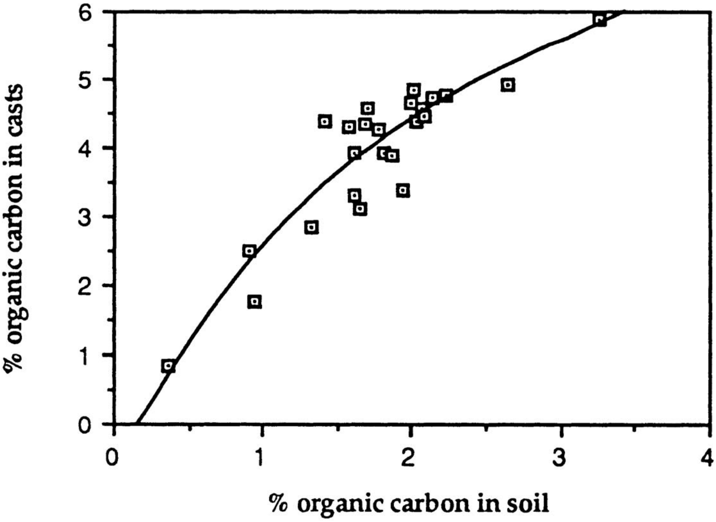

Figure 5 Relation between organic carbon concentration in the topsoil (0 to 5 cm) and in earthworm casts.

labeled fresh materials. In the case of *D. barteri* it is also necessary to acknowledge that the prunings are very recalcitrant, so that low relative uptake might rather be due to low release and availability. At 31 days after application of ^{15}N-labeled prunings, total recovery of ^{15}N in casts was 22.5 and 9.2% from *L. leucocephala* and *D. barteri,* respectively. These figures show that earthworms ingest decomposing, newly applied materials or decomposers associated with them, and that incorporation of nitrogen into earthworm casts may compete in a cropping system with crops requiring high supplies of nitrogen.

Earthworm Casts and Plant Growth

Earthworms can have positive effects on plant growth. Spain et al. (1992) showed that higher yields were associated with increased N uptake. Improved soil physical properties (Lal, 1988; Lal and Akinremi, 1983), as a consequence of burrowing and casting, may also contribute to enhanced crop performance. However, earthworms do not have positive effects on plant growth in all cases (Pashanasi et al., 1992).

Deposition of casts at the soil surface can generate a new soil layer of up to 0.55 cm thick within a year (Hauser, 1994). This layer has high concentrations of organic carbon and nutrients. Dry casts also have a high resistance to mechanical disintegration by raindrops. Thus a qualitative aspect of casting activity has to be considered. Experiments with *H. africanus* casts at Ibadan showed that casts withstood four times more rain events than soil aggregates before they started to disintegrate (Asawalam, unpublished).

In pot experiments, applying *H. africanus* casts to the soil surface or mixing ground casts into the soil, both increased maize growth and nitrogen uptake, as compared to maize in soil alone. Furthermore, cast application led to higher maize production in subsequent cropping phases, whereas area application did not (Mulongoy, 1990). In other experiments with *H. africanus* casts mixed with various amounts of topsoil, a linear increase of maize yield with an increasing proportion of casts in the mixture was shown (Asawalam, unpublished). Although the amount of nitrogen applied per pot tripled, the yield of maize increased by only 50%. Similar results were obtained at Mbalmayo using the same experimental approach. Nitrogen concentration in casts at Mbalmayo was only 58% higher than in the soil; however, the maize yield doubled in the pure casts compared with soil without casts. On the rather acid and poor Ultisol even small increases in nitrogen have a significant effect. Nitrogen availability from casts at Mbalmayo is apparently higher than from soil. Since this contradicts the results obtained at Ibadan and of other authors, it requires further investigation. Availability of nitrogen from casts is lower than from the topsoil at Ibadan. Thus a chemical or physical resistance to rapid mineralization and subsequent losses can be concluded. A stabilization of organic carbon by passage through earthworms has also been shown by Shaw and Pawluk (1986) and Lavelle et al. (1992). Since *H. africanus* casts contain up to four times more total nitrogen than the topsoil, an increased supply of nitrogen is possible even at lower release rates from the casts.

CONCLUSION

Earthworms play an important role in low-input agricultural systems. Their casting activity involves up to 11.6% of the organic carbon and 12.9% of the total nitrogen of the 0 to 15 cm topsoil in undisturbed or recovering systems. Earthworms are very sensitive to changes in the ecosystem, expressed by strongly reduced surface casting activity. In improved cropping systems earthworm activity can exceed that in the forest. This increase is due to the maintained groundcover and its reduced water consumption compared with forests. The negative impact of traditional cropping (lack of organic matter input through vegetation management) on casting becomes more pronounced as soil fertility decreases, while permanent groundcover becomes more important. The benefit of earthworm activity, apart from the effects on soil physical properties, is its concentration and deposition of large amounts of organic carbon and total nitrogen at the surface. Resources are placed at a location and in a form where (and in which) they are least likely to be lost. A firm conclusion on the effect of casts on plant nutrition is not yet possible.

In sustainable agricultural production systems the resource-conserving aspect of earthworm activity might be the more important one. *H. africanus* is active over a broad range of soil qualities and shows that it has the potential to improve or mediate the buildup of favorable soil properties. Thus, in accor-

dance with Lavelle et al. (1992), results from Ibadan show that earthworms are not merely a consequence of high soil fertility, but that they contribute to its buildup and maintenance.

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